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13. ABSTRACT *(Maximum 200 words)*
This project has succeeded to: generate new techniques, improve understandings of the physical foundations, and create algorithms for self-assembling systems in 2D and 3D.
We have developed a "self assembly tool box" consisting of a range of methods for micro-scale self-assembly in 2D and 3D. We have shown physical demonstrations of simple 3D self-assemblies which lead to integration of heterogeneous 3D systems via self-assembly. We have developed models and algorithms for quantitative analysis and prediction of self-assembly behavior, in particular for optimization of yield and assembly time. We have disseminated our findings in numerous conference presentations, invited talks, workshops, and started to develop IP in form of invention disclosures and patents.

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3D Programmable Micro Self-Assembly

Final Report

April 1, 2005 through March 31, 2005

Contract #FA9550-04-1-0257

March 31, 2005

PIs: Karl F. Böhringer, Babak A. Parviz, Eric Klavins

University of Washington

Seedling: Univ of Washington Self-Assembly Project Overview

Program Name: Seedling

Project Name: 3D Programmable Micro Self-Assembly

Project Start Date: 04/15/04

Project End Date: 02/14/05

Project Statement:

Development of self-assembling systems for 3-D functional devices at a cost of $300,000 over 10 months.

Status Statement:

This project has succeeded to

- generate new techniques
- improve understanding of the physical foundations
- create models and algorithms

for self-assembling systems in 2d and 3d.

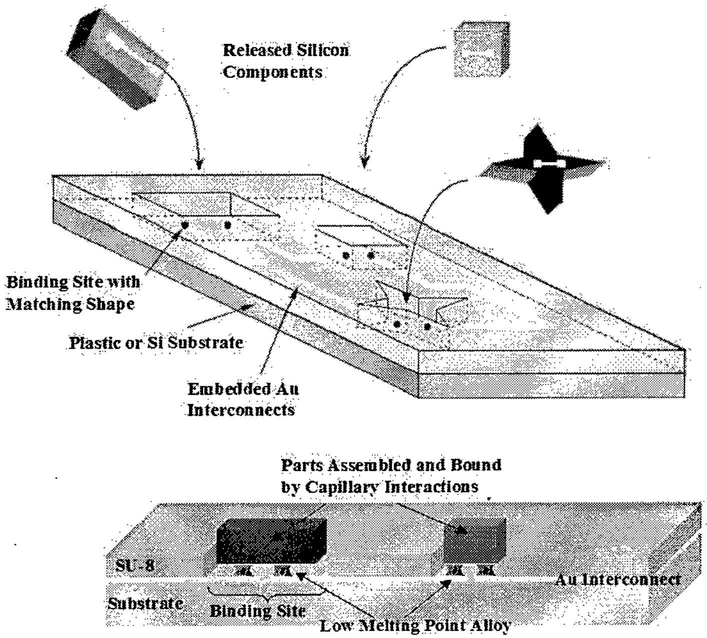
Summary of Accomplishments:

- We have developed a “self-assembly toolbox” consisting of a range of methods for micro-scale self-assembly in 2d and 3d
- We have shown physical demonstrations of simple 3d self-assemblies which lead to integration of heterogeneous 3d systems via self-assembly.
- We have developed models and algorithms for quantitative analysis and prediction of self-assembly behavior, in particular for optimization of yield and assembly time.
- We have disseminated our findings in numerous conference presentations, invited talks, workshops, and started to develop IP in form of invention disclosures and patents.

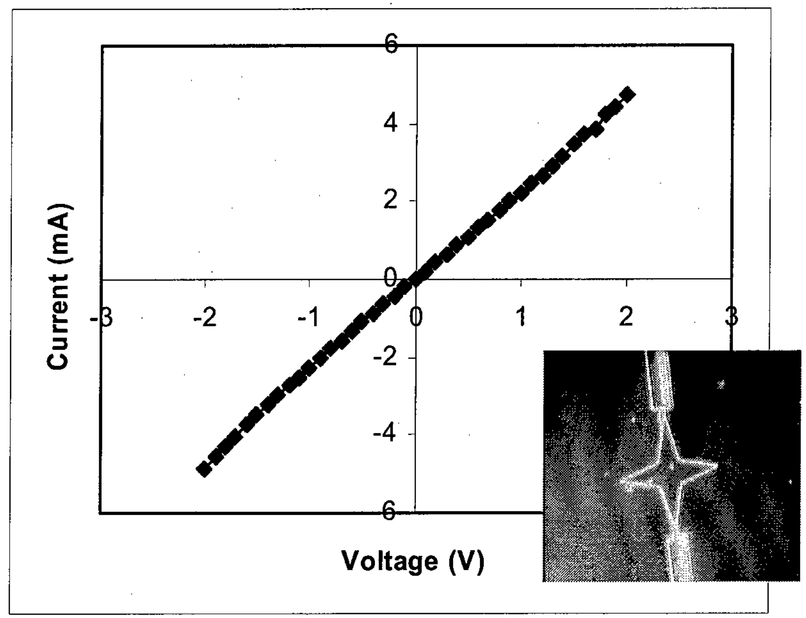
Self-assembly Toolkit:

Tools and Techniques for Self-Assembly in 2D and 3D

- Using capillary forces and shape recognition for shape-to-template assembly including electrical connectivity
- Self-assembly is driven by gravity and the capillary forces of the molten alloy joining the metallic pads of the components to the binding sites (templates) on the substrate to build the electrical connections.



Assembly by shape recognition.

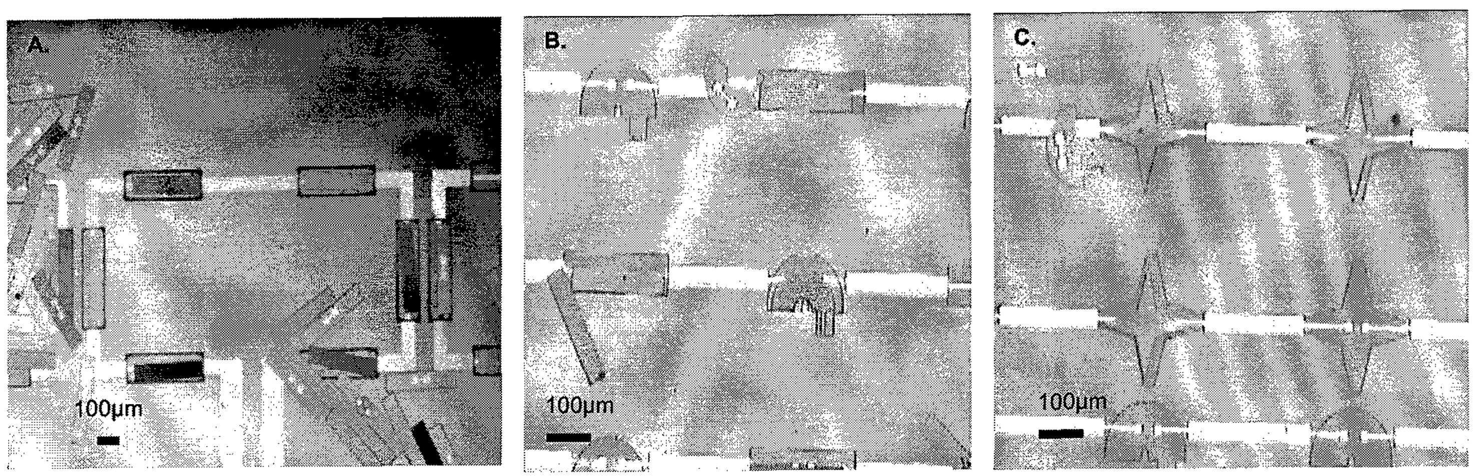


I-V curve of assembled component (inset) verifies electrical connection.

3D Programmable Micro Self-Assembly
Key Accomplishment #1.b

Self-assembly Toolkit:
Tools and Techniques for Self-Assembly in 2D and 3D

- Using capillary forces and shape recognition for shape-to-template assembly including electrical connectivity in water – discussion:



Assembled components—(A) homogeneous assembly (one type of component, (B) and (C) heterogeneous assembly (simultaneous assembly of multiple types of components).

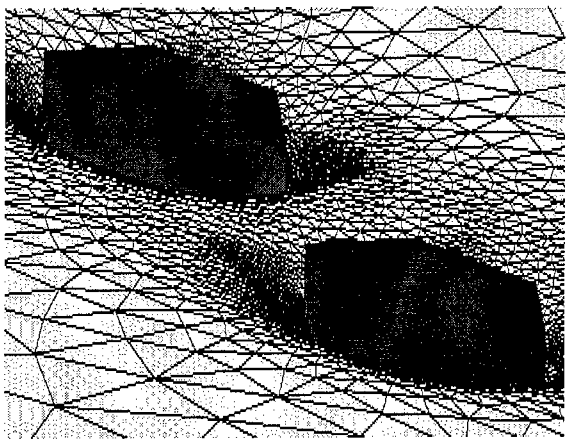
- All shapes can assemble thus allowing for selectivity.
- It has been found that different shapes give different rates of successful assembly due to the differences in mobilities of the different shapes.

3D Programmable Micro Self-Assembly
Key Accomplishment #1.c

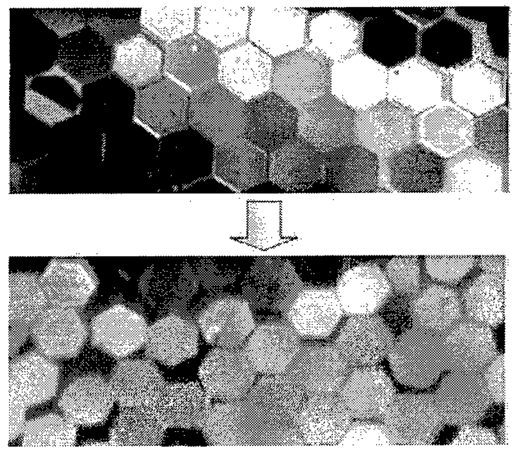
Self-assembly Toolkit:

Tools and Techniques for Self-Assembly in 2D and 3D

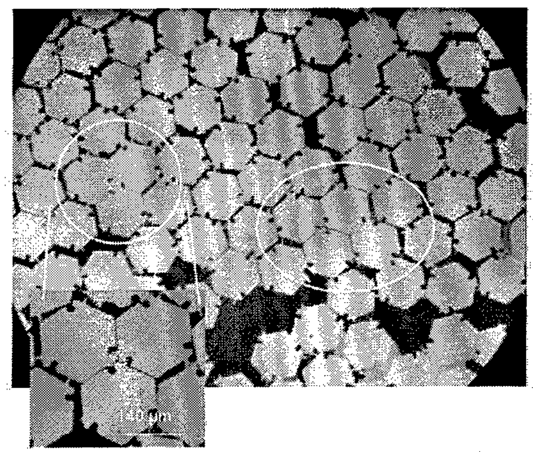
- Self-assembly and shape recognition at air-water interface
- The model, done with Surface Evolver, shows the energy minimization of two types of free-floating hexagonal part shapes as they are brought together.
- An important issue is to ensure that all parts have the correct orientation when they float at the interface (all face up or all face down).



Model of two hexagonal parts in Surface Evolver.



Oriented gold-side-facing-up, representing the successful manipulation of individual parts by reaching the stable energy minimal with agitated air-water interface.

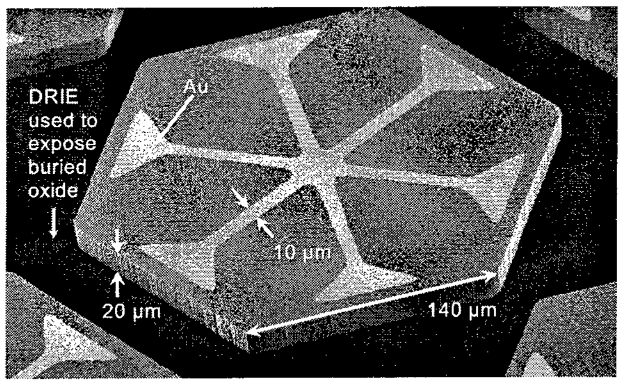


Experimental images of self-assembly with hexagonal "lock-and-key" parts. The local attraction of "lock and key features" leads to a low incidence of correct assembly.

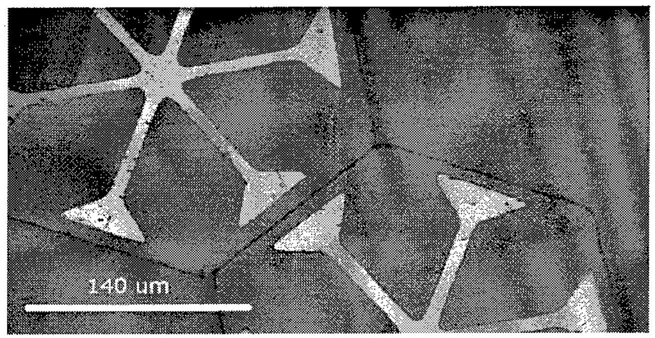
3D Programmable Micro Self-Assembly
Key Accomplishment #1.c

Self-assembly Toolkit:
Tools and Techniques for Self-Assembly in 2D and 3D

- Self-assembly and shape recognition at air-water interface – discussion:
- The use of shape recognition for self-assembly of floating microfabricated components at an air-water interface with the final goal of self-assembling an electrical network through this method.



SEM image of a microfabricated hexagonal part which demonstrates the feasibility of creating self-assembling circuit elements as a post-CMOS process.

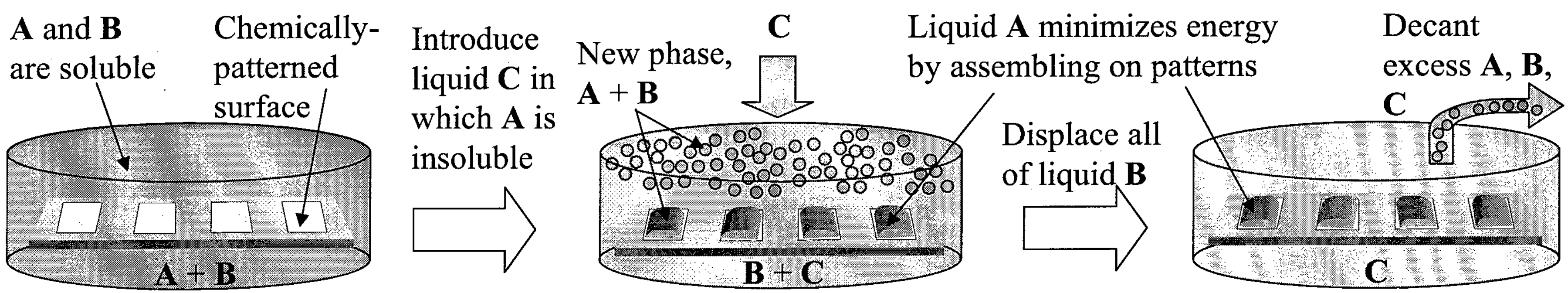


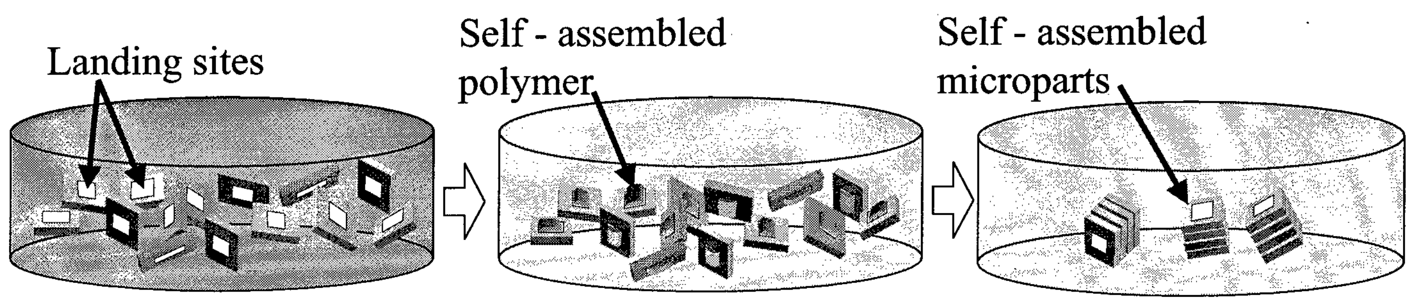
Micrograph depicting the bonding pad region between two adjacent parts. We expect to assemble solder on adjacent bonding pads to form electrical connections.

Self-assembly Toolkit:
Tools and Techniques for Self-Assembly in 2D and 3D

insoluble Liquid Energy Minimization (iLEM)

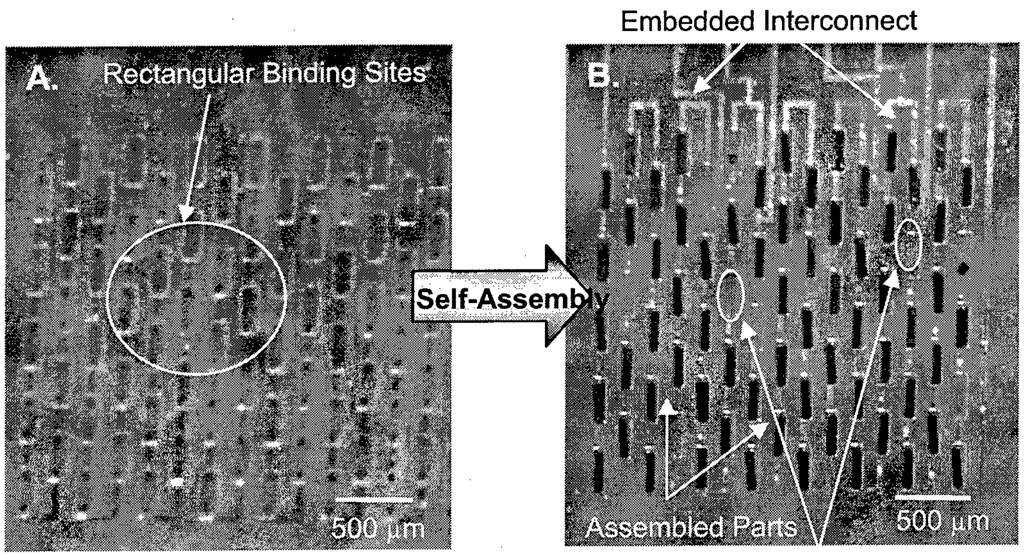
- Deposit material selectively on microfabricated parts utilizing a macroscopic solubility change to induce microscopic precipitation.
- Relies on solubility properties of three liquids. Liquid A is the liquid to be deposited, B is a solvent of A, and C is a solvent of B but not of A.
- By using a cross-linkable polymer as liquid A, solid structures can be formed in either A itself or by using A as an adhesive to link microfabricated parts.



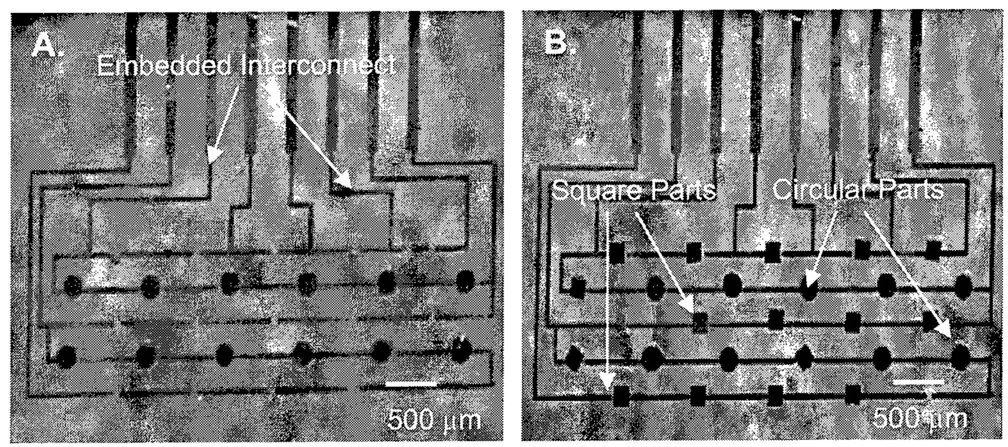


Self-assembly Toolkit:
Tools and Techniques for Self-Assembly in 2D and 3D

- High yield self-assembly experiments
  - Homogeneous and heterogeneous components (multiple types)
  - Polymer substrates



(A) Substrate before assembly with empty rectangular shaped binding sites, (B) substrate after self-assembly, with matching rectangular components. Color variation between (A) and (B) is due to change in background color as seen through the plastic substrate.

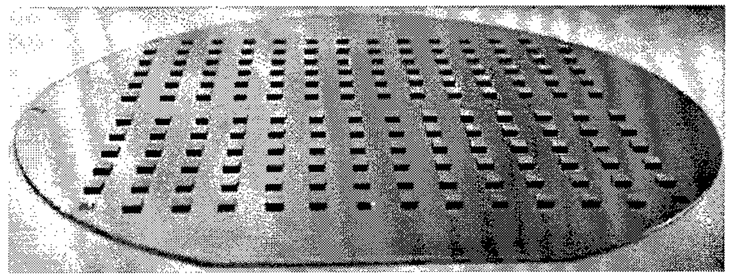


Assembled components— (A) homogeneous assembly (one type of component), (B) heterogeneous assembly (simultaneous assembly of multiple types of components).

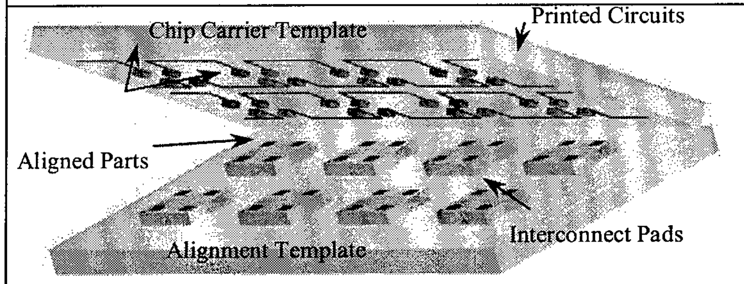
3D Programmable Micro Self-Assembly
Key Accomplishment #1.f

Self-assembly Toolkit:
Tools and Techniques for Self-Assembly in 2D and 3D

- High Yield Batch Packaging of Micro Devices with Uniquely Orienting Self-Assembly in Air
- To assemble microchips with multiple interconnect pads, the alignment orientation must be unique to achieve correct electrical connections to the chip carrier template.
- The major two steps: (1) face orienting and palletizing parts onto an alignment template; (2) trapping and uniquely aligning parts to binding sites.
- This work shows a complete assembly sequence from bulk part delivery to complete system integration.
- Furthermore, it presents a solution to unique alignment during self-assembly.



164 silicon parts self-aligned on a 4-inch alignment template.

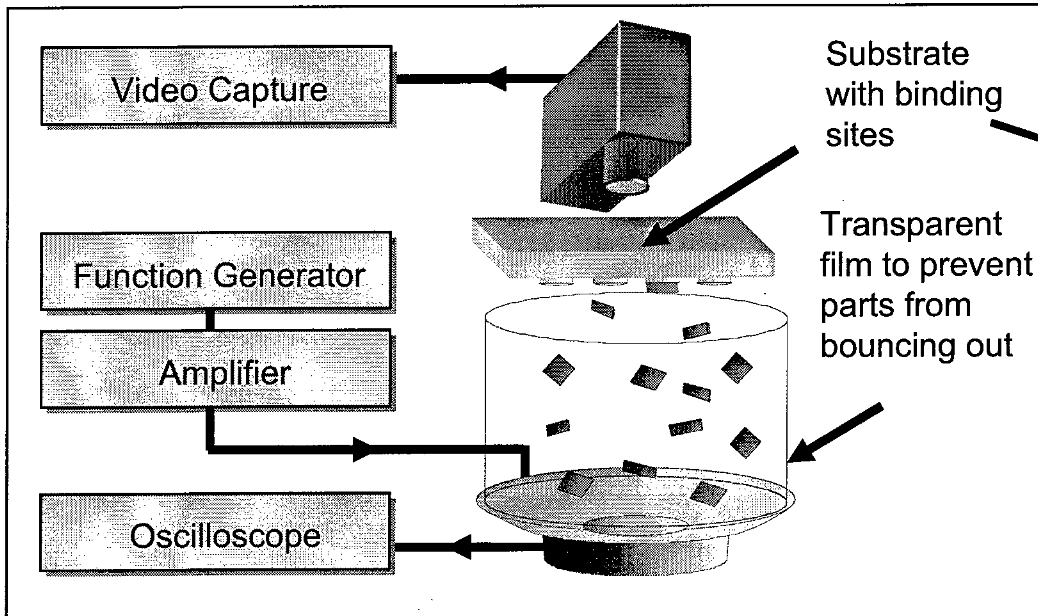


Wafer level flip-chip bonding (a well-established process in the IC industry) scheme for the mounting of uniquely aligned microchips onto a chip carrier template with electrical circuits.

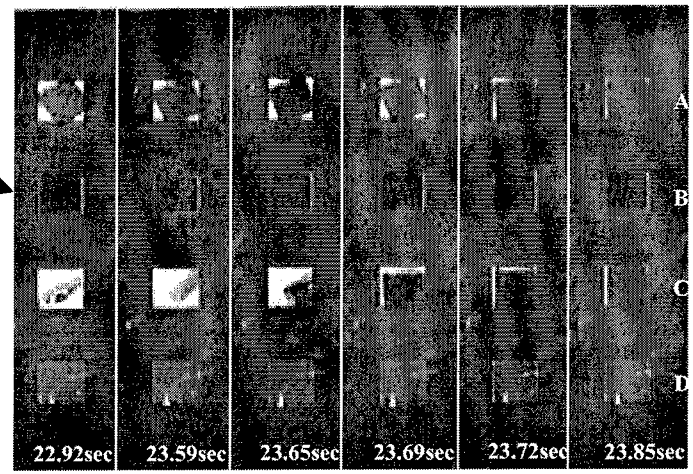
3D Programmable Micro Self-Assembly
Key Accomplishment #2.a

Towards 3D Self-assembly of Heterogeneous Systems

- A New Method for 3D Self-assembly Aided by Acoustic Agitation in Air
- We developed a gas/liquid interface based self-assembly technique that provides controlled acoustic agitation for parts delivery and "annealing" in air. It demonstrates fast (<30sec), high yield (>90%) performance.



The experimental setup



One column of the array shows: (A) alignment driven by surface tension, (B)(D) correctly aligned components, (C) vertical attachment being self-corrected by impacts.

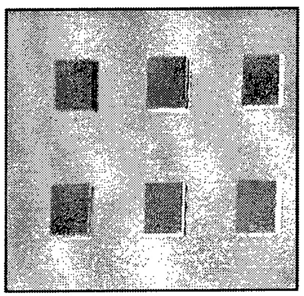
3D Programmable Micro Self-Assembly
Key Accomplishment #2.a

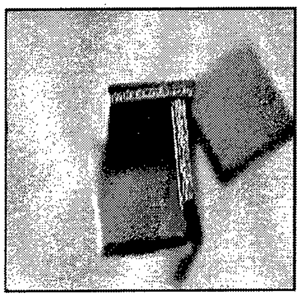
Towards 3D Self-assembly of Heterogeneous Systems

- A New Method for 3D Self-assembly Aided by Acoustic Agitation in Air – Discussion:
- Self-assembly by acoustic agitation demonstrates a fast, high-yield, self-correcting, in-air process without causing damage to tested comb drives.
- Extensions include:

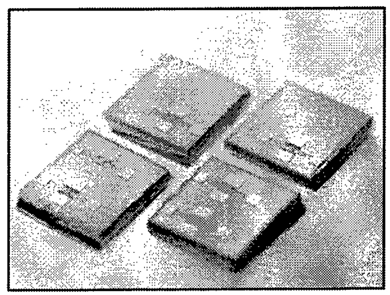
  (1) multi-batch assemblies with shadow masks blocking specific undesired sites in each batch, and

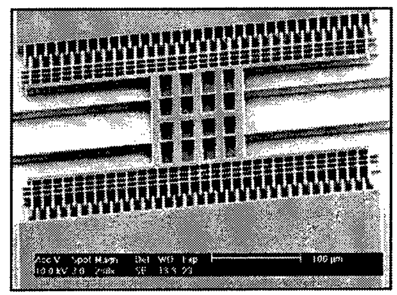
  (2) 3D / heterogeneous integration can be achieved in layered assemblies.
- This work constitutes one of the major original goals. It lays the foundation for a new, dry, 3D self-assembly process for parallel assembly of 3D microsystems.





Correct assemblies and 3D experiments ongoing





Tested MEMS chips and comb drives

3D Programmable Micro Self-Assembly Key Accomplishment #2.b

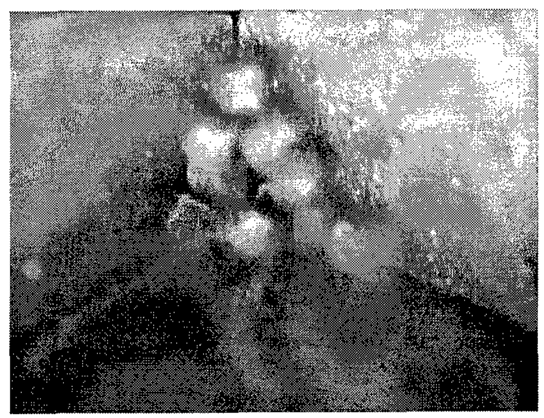
Towards 3D Self-assembly of Heterogeneous Systems

- 3D Self-assembly of Si Cubes Aided by Acoustic Shaker in Air
- We have developed a generally applicable process for 3d self-assembly with cube-shaped units. Currently, silicon parts are used with sizes between 1mm and 200μm side length. As the process develops and matures, other materials can be introduced.
- Furthermore, non-cubical components can also be assembled in this process if they are embedded in a sacrificial material forming a cube. The idea is that after assembly, the sacrificial material is removed and a scaffold assembly remains.

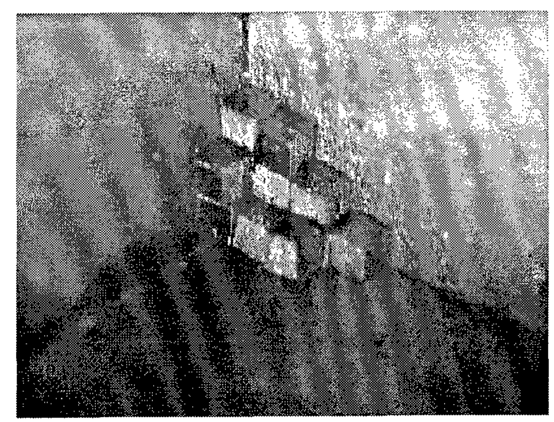
Discussion:

- 3D "crystals" of silicon cubes consisting of tens or hundreds of cubes can be achieved within seconds.

(a)



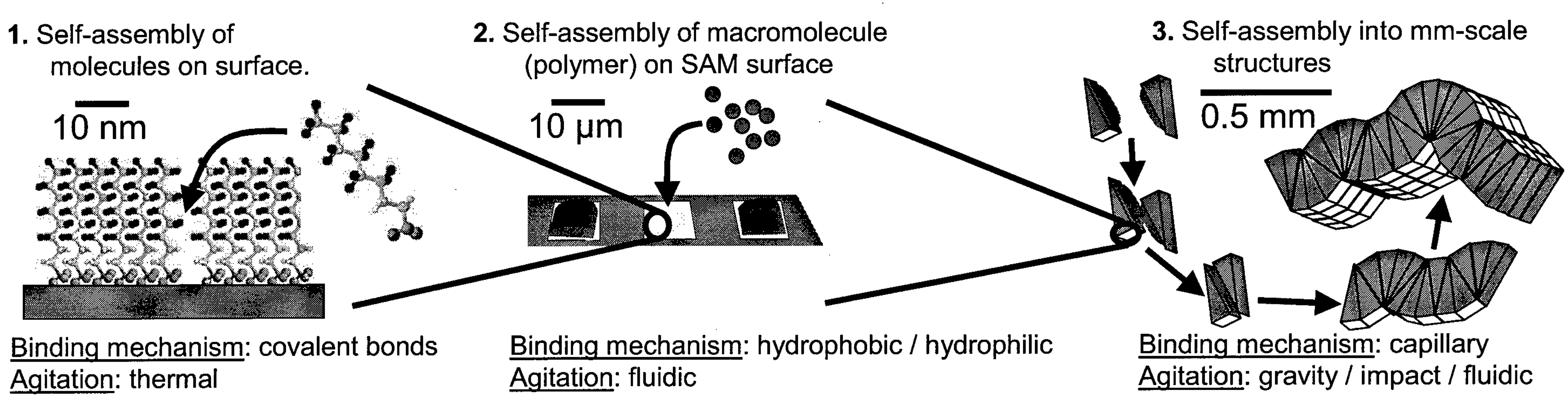
(b)



3d acoustic cube assembly (top view); (a) during agitation, (b) after agitation. 200μm silicon cubes are used in an assembly stage with 3 orthogonal plates of silicon mounted on a speaker.

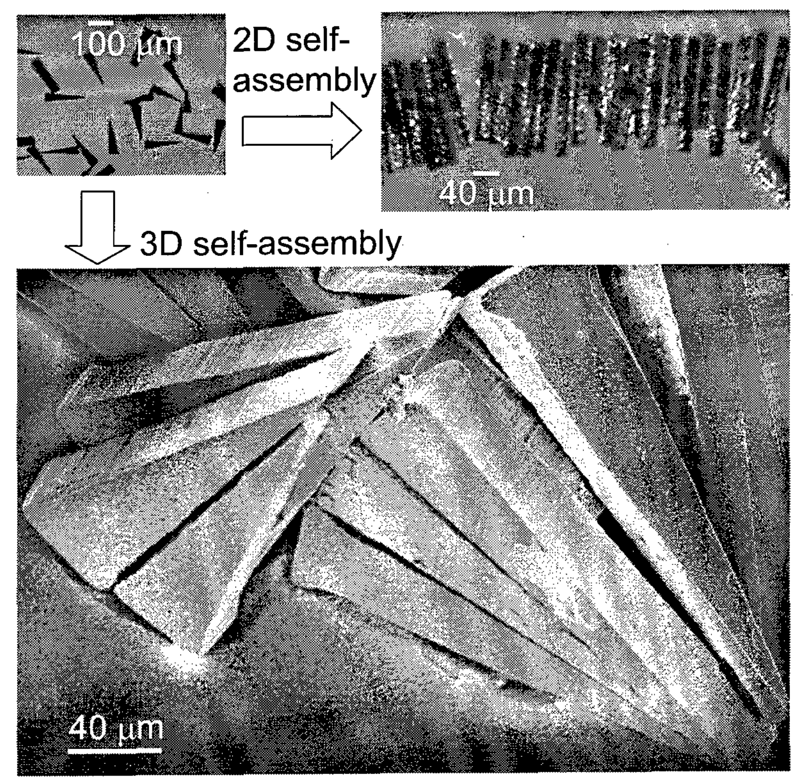
Towards 3D Self-assembly of Heterogeneous Systems

- 3D Self-assembly across scales
- Hierarchy of self-assembly across scales, including self-assembled monolayers (SAM), macromolecule assembly on a surface, and micropart self-assembly driven by capillary forces.
  - Left diagram: nanoscale SAM formation
  - Center diagram: self-assembly at the micron scale. The terminal groups of SAMs can express different values of macroscopically-observable surface energy. This surface energy differential can guide the selective self-assembly of macromolecules, or polymers, onto the surface.
  - Right diagram: microfabricated parts which have been functionalized by the deposition of polymer on specific surfaces. Capillary forces acting via the polymer regions on adjacent parts result in binding and self-assembly into mm-scale structures.



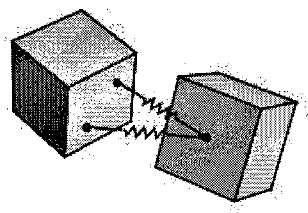
Towards 3D Self-assembly of Heterogeneous Systems

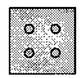
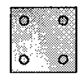
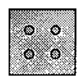
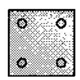
- <u>3D Self-assembly across scales</u>
- 3D self-assembled structure formation aided by capillary forces: structures at air-water interface shown on top; structures immersed in water with cured polymer adhesive shown at bottom.



Self-assembly Models and Algorithms

- The Model for Complex Self-assembly Based on Point Attractors
- We have built a simulation of the cube apparatus based on a model wherein “point attractors” located on the faces of each cubical part model the attraction of, for example, hydrophobic faces toward each other.
- Using the simulation we have explored the relationship between point-attractor placement, agitation energy and assembly types and yield.



Binding force		
	3.8	2.5
	2.5	3.9

The point attractor model: Point binding sites on each face attract points on other faces. By placing points in various patterns, we can model binding interactions of various strengths. By agitating at different energies, we can select certain binding interactions and not others.

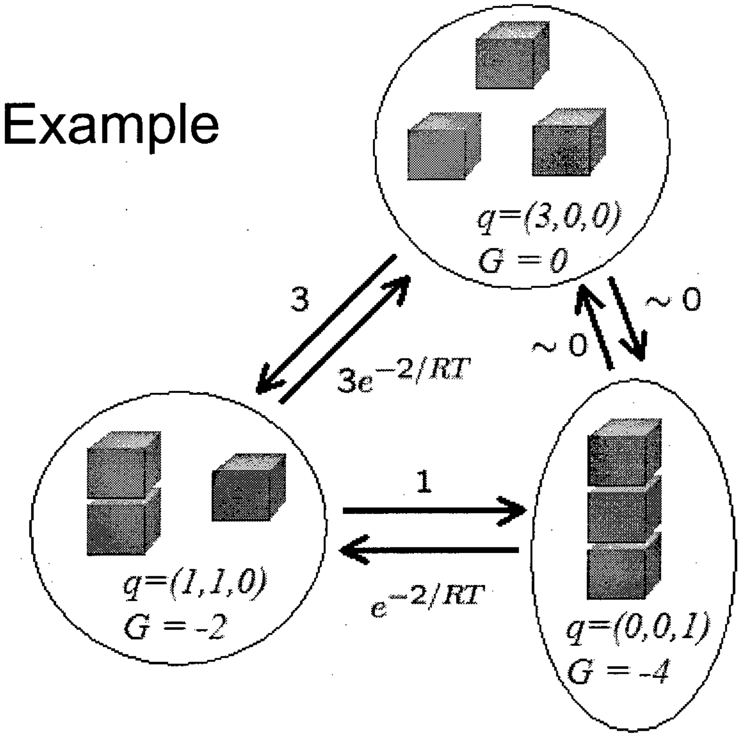
Discussion: The simulation allows us to quickly validate theoretical predictions of the 3D cube assembly process.

3D Programmable Micro Self-Assembly
Key Accomplishment #3.b

Self-assembly Models and Algorithms

- <u>Describing The Yields of Self-assembly as a Stochastic Markov Process</u>
- Klavins has developed an abstract topological model of the yields of self-assembly processes that is based on *graph grammars and a thermo-dynamic approach*. The model captures many of the essential properties of self-assembly processes, while not relying on any particular physical model.

Example



- Choose forward rates via combinatorics to account for flux
- Choose backward rates so that

$$\ln \frac{k_{ji}}{k_{ij}} = \frac{\Delta G_{ij}}{RT}$$

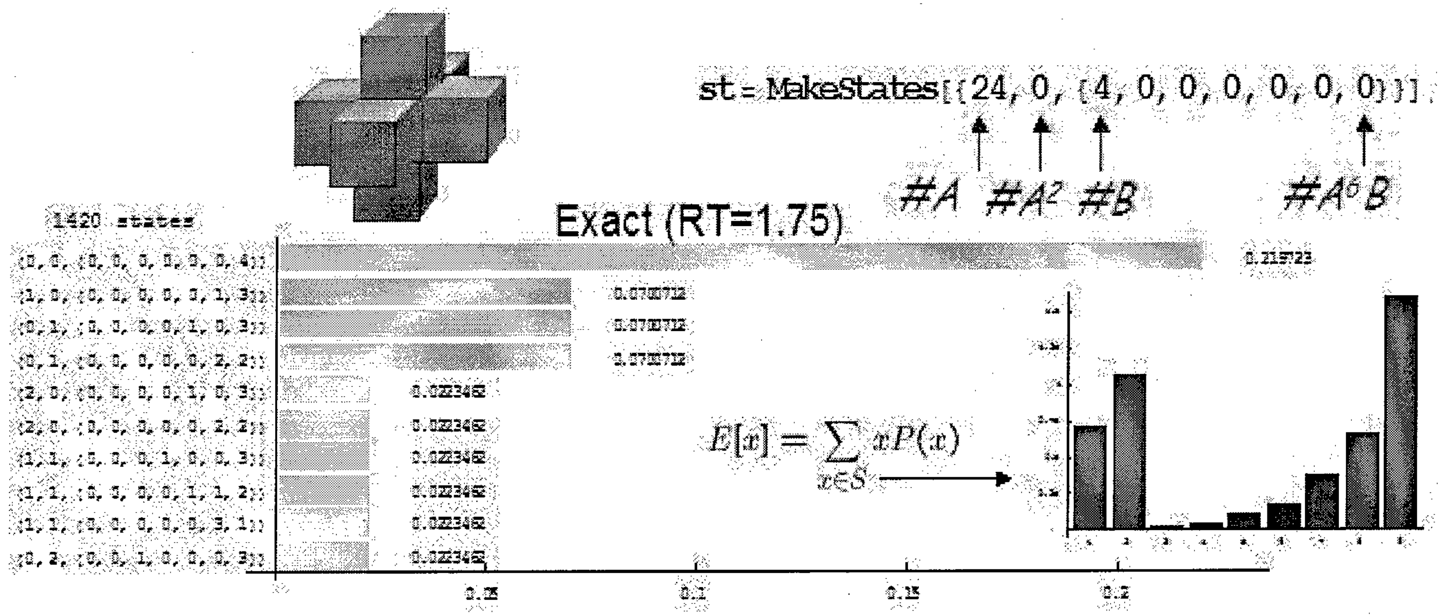
- This defines a jump Markov process where

$$P_{i,j}(\tau) = K_{i,j} e^{-K_i \tau / RT}$$

- As long as the rates have the right ratios, the steady state is given by *(a)*.

Self-assembly Models and Algorithms

- Describing The Yields of Self-assembly as a Stochastic Markov Process



Discussion:

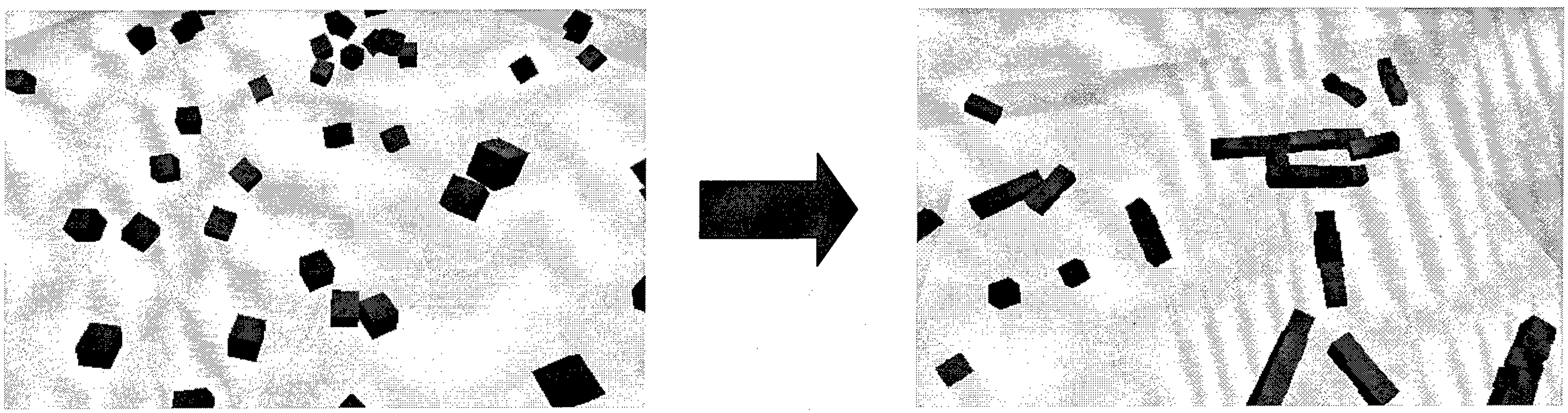
- We can generate rule systems and estimate the yield for desired assembly as *stable* (unchanging) objects. The only other objects that emerge are *unstable* subassemblies of the desired one, which must eventually grow.

Self-assembly Models and Algorithms

Simulation and Analysis of Dry Cube Self Assembly

Simulated Experiments:

- Simulated use of photoresist as binding agent between micro-cubes.
- Analysis of coefficient of restitution on total system energy
- Patterning of binding sites on cube faces



Honors and Awards to PIs during Contract Period

- Karl F. Böhringer, Japan Society for the Promotion of Science (JSPS) Invitational Fellowship for Research in Japan, 2004.
- Karl F. Böhringer, IEEE Robotics and Automation Society Academic Early Career Award "For contributions to physical geometric algorithms and MEMS, with applications to self-assembly and part manipulation", 2004.

- Babak A. Parviz, selected by the National Academies to Participate in the Keck Future Initiative 2004 "Designing Nanostructures at the Interface Between Biomedical and Physical Systems".
- Babak A. Parviz, nominated for the Outstanding Teaching Award, Electrical Engineering Department, University of Washington, May 2004.
- Babak A. Parviz, editor's choice of the Journal Science (Jan 30th 2004) for the paper: S. K. Sia, V. Linder, B. A. Parviz, A. Siegel, G. M. Whitesides, "An Integrated Approach to a Portable and Low-Cost Immunoassay for Resource-Poor Settings", Angewandte Chemie International Edition, v 43, n 4, Jan. 2004, p 498-502.

- Eric Klavins, NSF CAREER Award, 2004.

Seedling: Univ of Washington Self-Assembly Visuals

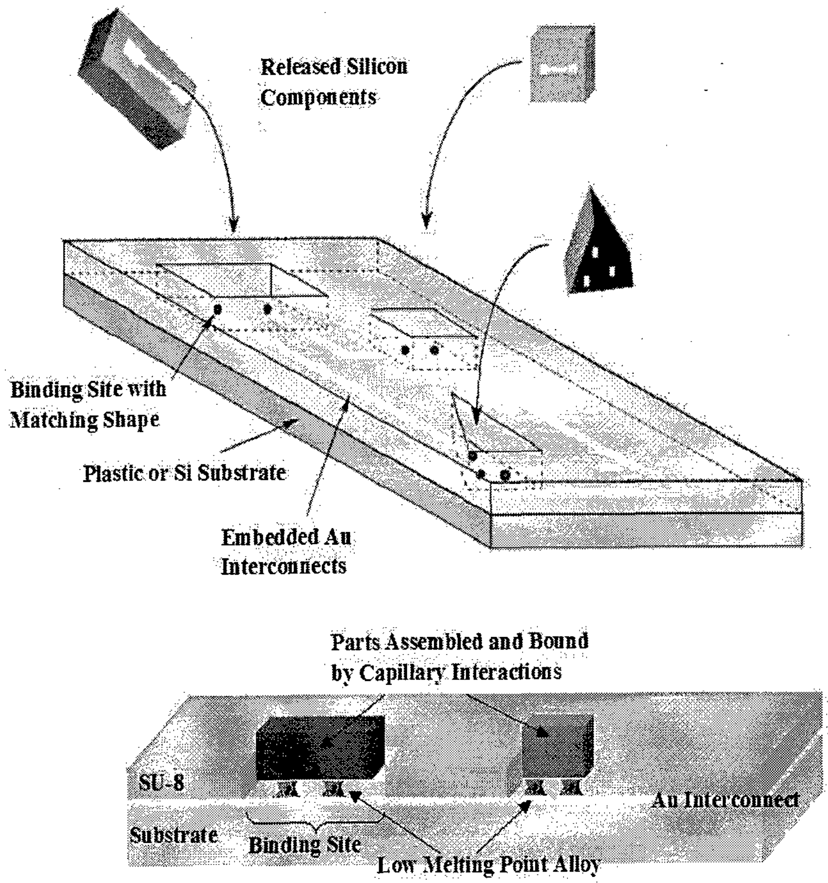
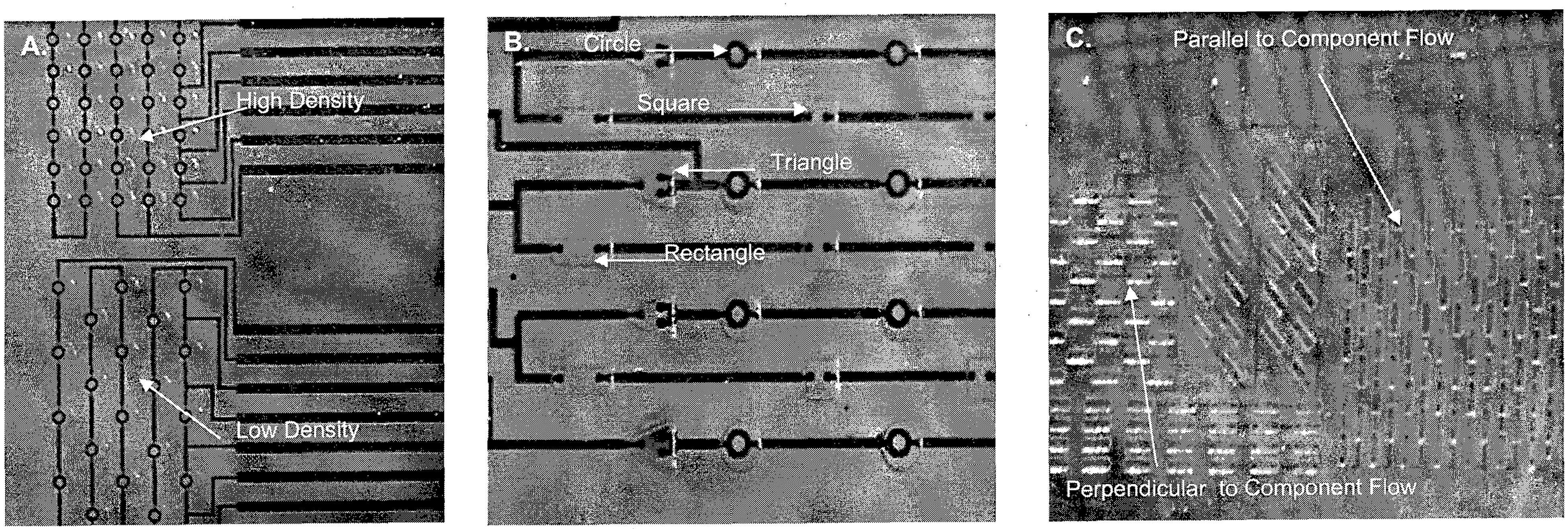


Illustration of Assembly Process. Silicon components self-assemble at complementary shaped binding sites to complete the electrical connection on a plastic substrate.

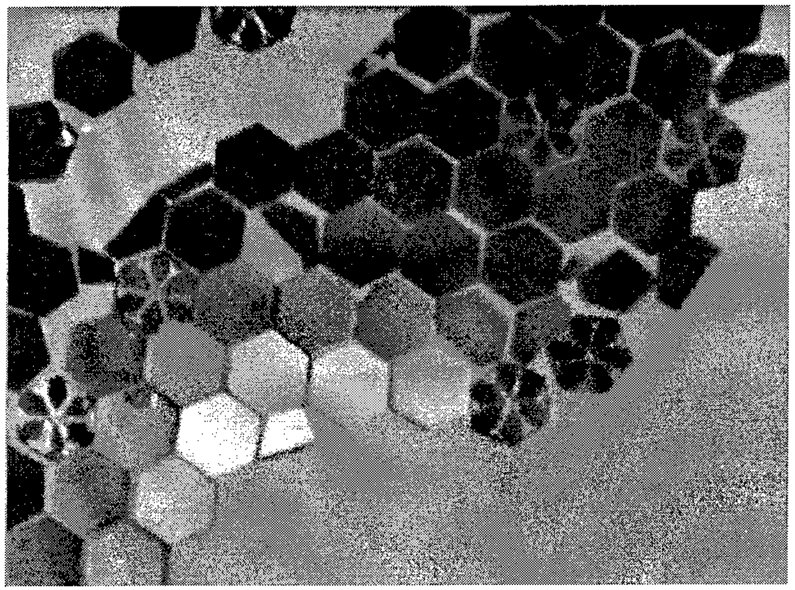
Polyester substrate with interconnects and matching binding sites.

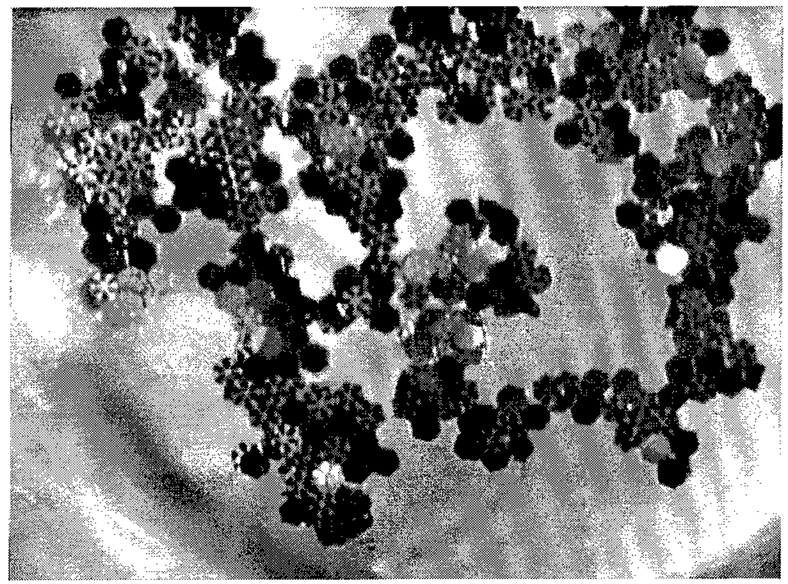
Seedling: Univ of Washington Self-Assembly Visuals



A) Circular binding sites, both high density (above) and low density (below), B) Four different binding site shapes integrated into same network, C) Rectangular binding sites, testing how orientation affects the assembly rate.

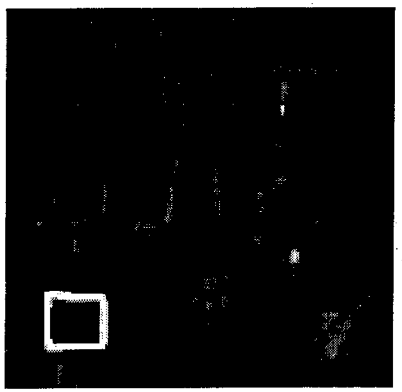
Seedling: Univ of Washington Self-Assembly Visuals



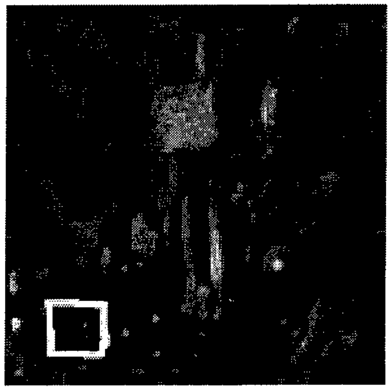


Examples of two-dimensional self-assembly at an air water interface after polymer material was deposited with iLEM.

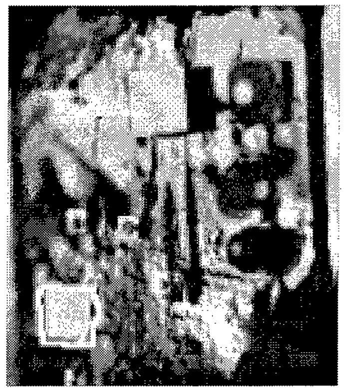
Seedling: Univ of Washington Self-Assembly Visuals



(a) 0°

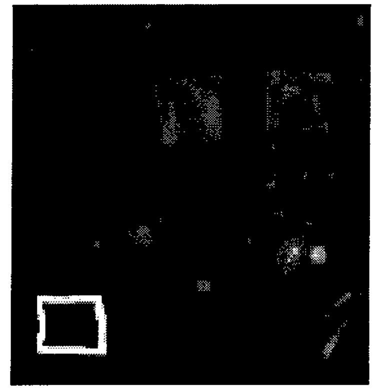


(b) 15°



(c) 30°

(d) 45°



(e) 0°

A sequence of calibration images for photometric stereo (PMS) with only the blue light source turned on. Each image shows a plate with various components mounted on it, rotated different amounts relative to the camera.
(a)-(c) Note the outlined area which corresponds to the edge of a silicon rectangle.
(d) Same plate with all three light sources turned on.

Seedling: Univ of Washington Self-Assembly Deliverables

- <No deliverables are currently on listed on your project website. Please list your deliverables/milestones using the format below.>

Deliverable	Type	Date	Description
Microfabrication: simple shape recognition	Minor	2/14/2005	Simple shape recognition/selection with goal of active silicon circuits in plastic substrates.
Microfabrication: 2-D self assembly	Minor	2/14/2005	Through selective polymer SAM coating and manipulation of surface tension. Sides of parts are bonded.
Microfabrication: 2-step shape recognition	Minor	2/14/2005	Vibration of parts over a template. Larger shape + 2nd smaller shape for precision.
Microfabrication: 3-D agitated self assembly	Minor	2/14/2005	Agitation analogous to increasing temp. Slowing down agitation analogous to annealing.
Modeling and rules synthesis	Minor	2/14/2005	Klavins modeling to understand and develop predictive theories and design rules.
Final report	Major	2/14/2005	

Seedling: Univ of Washington Self-Assembly Team

- <The following contacts are currently on listed on your project website. Please complete, verify, and add team information as necessary.>

Name	Organization	Project Role	Email
Karl Bohringer	University of Washington	PI	karl@ee.washington.edu
Eric Klavins	University of Washington	PI	klavins@ee.washington.edu
Babak Parviz	University of Washington	PI	babak@ee.washington.edu
Kerwin Wang	University of Washington	Postdoc - Bohringer	
Xiaorong Xiong	University of Washington	Postdoc - Bohringer	
Jiandong Fang	University of Washington	Grad student - Bohringer	
Sheng-Hsiung Liang	University of Washington	Grad student - Bohringer	
Dick Kreisberg	University of Washington	Grad student - Klavins	
Nils Napp	University of Washington	Grad student - Klavins	
Chris Morris	University of Washington	Grad student - Parviz	
Sean Stauth	University of Washington	Grad student - Parviz	

- <List any team changes that occurred in the last quarter below.>

Team departures:

- N/A

Team additions:

- N/A

Seedling: Univ of Washington Self-Assembly Contracts and Subcontracts

- <The following contracts/subcontracts are currently on listed on your project website. Please complete, verify and add contracts/subcontracts as necessary.>

Contractor	Contractee	Type	Date signed	Date effective	End date	Value
University of Washington	<who is your agent for this contract??>	Prime Contract		04/15/04	02/14/05	$300,000.00

Seedling: Univ of Washington Self-Assembly
Significant Briefings

- <No briefings are currently on listed on your project website. Please list any briefings you've given over the course of your project.>

Briefing To	Briefing By	Date	Comments
John Evans	Babak Parviz	11/24/04	
Steven Ho	Karl Bohringer	8/5/04	

Seedling: Univ of Washington Self-Assembly Invoiced Expenses

- <The following list of invoiced expenses is currently listed on your project website. Please complete, verify, and add data as necessary.>

Invoice #	Invoice Date	Period Start	Period End	Amount
GC589060	7/29/2004			$100,000.00
GC589061	7/29/2004			$100,000.00
GC589062	11/15/2004			$100,000.00
Total				**$300,000.00**

Seedling: Univ of Washington Self-Assembly Expenditure Plan

- <The following expenditure plan is currently listed on your project website. Please complete, verify, and add data as necessary.>

Month	Amount
7/29/2004	$100,000.00
7/29/2004	$100,000.00
11/15/2004	$100,000.00
Total	**$300,000.00**

Seedling: Univ of Washington Self-Assembly Publications

Conference Publications (Böhringer)

- Jiandong Fang, Karl F. Böhringer, "Uniquely Orienting Dry Micro Assembly by Two-Stage Shape Recognition". The 13th International Conference on Solid-State Sensors and Actuators (Transducers'05), Seoul, Korea, June 5-9, 2005.
- Jiandong Fang, Sheng-Hsiung Liang, Kerwin Wang, Xiaorong Xiong, Karl F. Böhringer, "Self-Assembly of Flat Micro Components by Capillary Forces and Shape Recognition." *2nd Annual Conference on Foundations of Nanoscience: Selfassembled Architectures and Devices (FNANO),* Snowbird, UT, April 24-28, 2005.
- Neil A. Bernotski, Xiaorong Xiong, Kerwin Wang, Nels E. Jewell-Larsen, and Karl F. Böhringer, "Formation of Two-Dimensional Colloidal Sphere Arrays on Micro-Patterns." *2nd Annual Conference on Foundations of Nanoscience: Selfassembled Architectures and Devices (FNANO),* Snowbird, UT, April 24-28, 2005.
- Jiandong Fang, Karl F. Böhringer, "High Yield Batch Packaging of Micro Devices with Uniquely Orienting Self-assembly". *IEEE Conference on Micro Electro Mechanical Systems (MEMS)*, Miami Beach, FL, January 30 – February 3, 2005.
- Sheng-Hsiung Liang, Kerwin Wang, Karl F. Böhringer, "Self-assembly of MEMS Components in Air Assisted by Diaphragm Agitation". *IEEE Conference on Micro Electro Mechanical Systems (MEMS)*, Miami Beach, FL, January 30 – February 3, 2005.
- Jiandong Fang, Kerwin Wang, Karl F. Böhringer, "Self-assembly of Micro Pumps with High Uniformity in Performance." *Solid State Sensor, Actuator, and Microsystems Workshop (Hilton Head'04),* Hilton Head Island, SC, June 6-10, 2004.
- Xiaorong Xiong, Sheng-Hsiung Liang, Karl F. Böhringer, "Geometric Binding Site Design for Surface-Tension Driven Self-Assembly." *IEEE International Conference on Robotics and Automation (ICRA),* New Orleans, April 26 – May 1, 2004.
- Xiaorong Xiong, Kerwin Wang, Karl F. Böhringer, "From Micro-Patterns to Nano-Structures by Controllable Colloidal Aggregation at Air-Water Interface." *IEEE Conference on Micro Electro Mechanical Systems (MEMS)*, Maastricht, Holland, January 25-29, 2004.
- Sheng-Hsiung Liang, Xiaorong Xiong, Karl F. Böhringer, "Towards Optimal Designs for Self-alignment in Surface-tension Driven Micro-assembly." *IEEE Conference on Micro Electro Mechanical Systems (MEMS)*, Maastricht, Holland, January 25-29, 2004.

Submitted for review:

Short Courses and Workshops (Böhringer)

- "Self Assembly Processes for Device Attachment: Trends & Challenges", invited talk, *Workshop on Self Assembly Processes for Nano devices and modules*, A*star Institute of Microelectronics (IME), 11 Science Park Road, Singapore Science Park II, Singapore 117685, April 1, 2005.
- "Next Generation Packaging Workshop." Short course, *Industrial Technology Research Institute (ITRI),* Hsin Chu, Taiwan, November 10-11, 2004.

Conference Publications (Klavins)

- N. Napp, J. Bishop, E. Klavins, "Graph Grammars and Robotic Self-Assembly". *2nd Annual Conference on Foundations of Nanoscience: Selfassembled Architectures and Devices (FNANO),* Snowbird, UT, April 24-28, 2005.
- Eric Klavins. Universal self-replication using graph grammars. In *The 2004 International Conference on MEMs, NANO and Smart Systems*, Banff, Canada, 2004.
- Eric Klavins, Robert Ghrist, and David Lipsky. Graph grammars for self-assembling robotic systems. In *Proceedings of the International Conference on Robotics and Automation*, April 26 – May 1, 2004.
- Eric Klavins. Directed self-assembly using graph grammars. In *Foundations of Nanoscience: Self Assembled Architectures and Devices*, Snowbird, UT, April 2004.

Submitted for review:

Seedling: Univ of Washington Self-Assembly Publications

Conference Publications (Parviz)

- Christopher J. Morris, Sean A. Stauth, and Babak A. Parviz, "Using Capillary Forces for Self-Assembly of Functional Microstructures", *Foundations of Nanoscience Conference (Self-assembled architectures and devices)*, Snowbird, Utah April 24-28, 2005
- Sean A. Stauth, and Babak A. Parviz," Self-assembled silicon networks on plastic", to be presented at *13th International Conference on Solid-state Sensors, Actuators, and Microsystems (Transducers' 2005)*, Seoul, Korea June 5-9, 2005
- Babak A. Parivz, "Self-assembly as an engineering concept across the size-scale", (Invited), *National Academies Keck Future Initiative Conference: "Designing Nanostructures at the Interface Between Biomedical and Physical Systems"*, Irvine, CA, November 18th-21st 2004
- Jianchun Dong, Hong Ma, Alex Jen, Babak A. Parviz, "Using self-assembly for the construction of nano-scale lateral transport molecular electronic devices and micro-scale silicon-based networks", Invited paper, presented at *Optics East (Nanosensing: Materials and Devices)*, Philadelphia, October 25th-28th 2004
- Sean Stauth, Christopher Morris, Babak Parviz, "Guided and Unconstrained Self-Assembled Silicon Circuits", *Evolvable Hardware 2004*, Seattle, WA, June 24th-26th 2004.

Submitted for review:

- Christopher J. Morris, Harvey Ho, and Babak A. Parviz, "Bridging Between Nano- and Micro-Scales For System Integration: Controlled Capillary Force-Driven Self Assembly", submitted to the *5th IEEE Conference on Nanotechnology*, to be held in Nagoya, Japan July 11-15, 2005
- Sean A. Stauth, and Babak A. Parviz," Integration of Silicon Circuit Components Onto Plastic Substrates Using Fluidic Self-Assembly", submitted to *The 2005 International Conference on MEMS, Nano, and Smart Systems*, to be held in Banff, Alberta, Canada July 24-29, 2005
- Christopher J. Morris, Harvey Ho, and Babak A. Parviz, "Using Insolubility Wave-front for Polymer Deposition on Self-Assembling Microfabricated Parts", submitted to *The 2005 International Conference on MEMS, Nano, and Smart Systems*, to be held in Banff, Alberta, Canada July 24-29, 2005

Journal Publications

Submitted for review:

- Jiandong Fang, Karl F. Böhringer, "Wafer Level Packaging Based on Uniquely Orienting Self-Assembly." Submitted to *ASME/IEEE Journal of Microelectromechancial Systems*, submitted December 21, 2004.
- Jiandong Fang, Kerwin Wang, Karl F. Böhringer, "Self-Assembly of PZT Actuators for Micro Pumps with High Process Repeatability." Submitted to *ASME/IEEE Journal of Microelectromechancial Systems*, submitted December 21, 2004.
- Eric Klavins, Robert Ghrist, and David Lipsky. A grammatical approach to self-organizing robotic systems. Sumbitted to the *International Journal of Robotics Research*, 2004.
- Christopher J. Morris, Sean S. Stauth, and Babak A. Parviz, "Self-assembly for micro and nano scale packaging: steps towards self-packaging", submitted to the *IEEE Transactions on Advanced Packaging.*

Seedling: Univ of Washington Self-Assembly Patents and Disclosures

Title	Action Type	Action Date
Surface Tension Powered Self-Assembly of Electro-Mechanic Micro Chips with High Process Repeatability	Disclosure Filing	5/21/2004
High Yield Batch Packaging of Microchips with Uniquely Orienting Self-Assembly	Disclosure Filing	8/23/2004
	Patent Award	